A novel FSI approach for the study of the aorta hemodynamics: an integrated imaged based and RBF mesh morphing technique

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Introduction

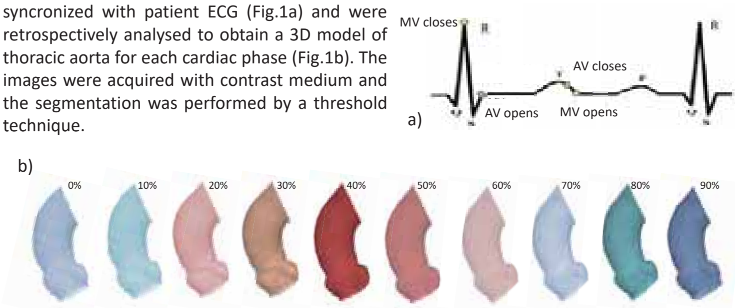
Numerical simulations have proven to be a useful instrument to assess the complexity of vascular flows and to overcome the low accuracy in the estimation of hemodynamic indices in-vivo. CFD simulations for thoracic aorta represent an effective strategy to investigate the hemodynamics even if the rigid wall assumption involves a not negligible limitation due to the no consideration of geometry changes and wall compliance. FSI simulations overcome this limitation but involve some assumption, in fact they require the definition of material properties, that are not easy to be defined in-vivo. RBF mesh morphing technique is already applied in in the cardiovascular field in literature and it turned out to be an effective tool to cope large vessel deformation [1].

Aim - To investigate the feasibility of a novel numerical simulation strategy based on **CT images** and **RBF mesh morphing technique** to cope the aortic wall deformation during cardiac cycle without FSI simulations

Image processing

Volumetric CT datasets were acquired syncronized with patient ECG (Fig.1a) and were retrospectively analysed to obtain a 3D model of thoracic aorta for each cardiac phase (Fig.1b). The images were acquired with contrast medium and the segmentation was performed by a threshold technique.

Figure 1



RBF mesh morphing technique and prescribed wall motion simulation (FSI_{RBF})

Step 1 – RBF solutions (baseline -> model *n*)

The mesh of the aortic model at 0% of cardiac cycle (baseline configuration) is used as reference to accomplish the projection onto the target configuration (each other model phases).

Step 2 – RBF incremental solutions

A set of RBF incremental solutions were created by processing the RBF solutions previous generated in step 1. The nodes of the parts which the target projection was applied to, were driven by a node-to-node displacement.

Step 3 – FSIRBF simulation

RBF incremental solutions were combined to apply morphing sequentially during the transient simulation in function of time, so as to automatically synchronize the actual movement of the vessel with the pulsating fluid flow (Fig.2). During the simulation process all RBF incremental solutions were activated with different weights as described the equations below.

$$RBF(t) = RBF_{0-20} \oplus RBF_{20-40} \oplus RBF_{40-60} \oplus RBF_{60-80} \oplus RBF_{80-0}$$

$$RBF_{t_1-t_2} = \begin{cases} 0 & t < t_1 \\ \frac{t-t_1}{t_2-t_1} & t_1 \leq t \leq t_2 \\ 1 & t > t_2 \end{cases}$$

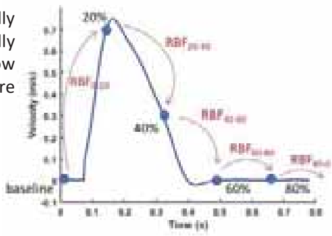


Figure 2

Simulation setup

Tetrahedral elements and four inflation layers were used, the blood was assumed as a Non-Newtonian incompressible fluid (density of 1060 kg/m3) adopting the Carreau model. A blood flow velocity inlet profile was assigned to the aortic inlet and a pressure outlet condition was assumed for the four outlets (supra-aortic vessels and descending aorta) implementing a lumped 3-element Windkessel model [2] (Fig.3). The Ansys fluent solutor and RBF morph were used for the simulation.

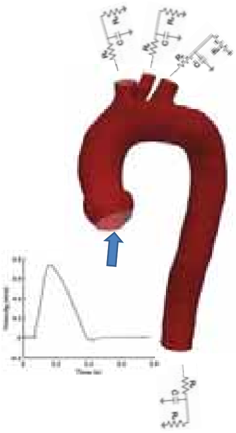


Figure 3

Results – RBF mesh morphing technique

The effectiveness of method application on our case was evaluated based on the achievement of target geometry and mesh perspective.

In the first assessment a comparison between target geometry and the final RBF morphing configuration was performed for each model of cardiac phases. The distance between started and target geometries reached at maximum 0.21 mm for the case of 20% and the majority of cell vertex had a distance lower then 0.04 mm (Fig.4). The mesh quality was evaluated in terms of skewness metric, the skewness value was increased with mesh deformation, the worst case was at 40% of cardiac cycle, nevertheless only two cell showed a value greater then 0.95 without problem for simulation convergence (Fig.5).

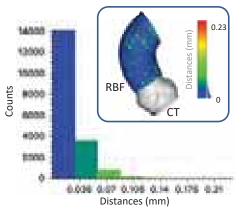


Figure 4

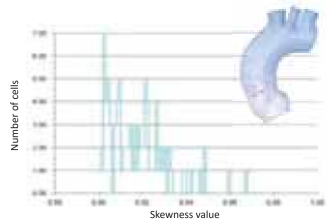


Figure 5

Results - FSIRBF

Figure 6 reports velocity streamlines for the CFD approach and for the FSIRBF strategy at systolic peak (t1), at late systolic phase (t2) and at diastolic phase (t3); the different dimension of ascending aorta for this second case is visible. Velocity magnitude results in a selected cross section at the same times are reported in figure 7, differences are present already at systolic peak and increase in the late systolic phase up to the diastolic phase. The WSS maps are depicted in figure 8, maximum differences are showed at t3 time duo the greatest vessel deformation at this phase.

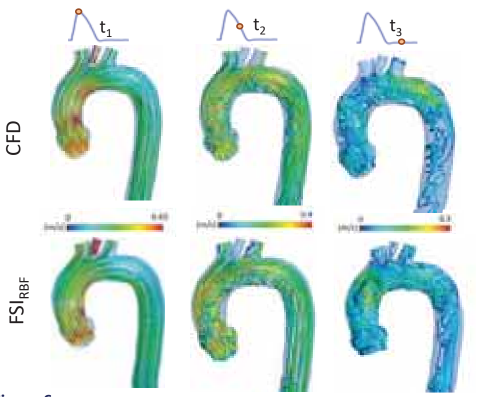


Figure 6

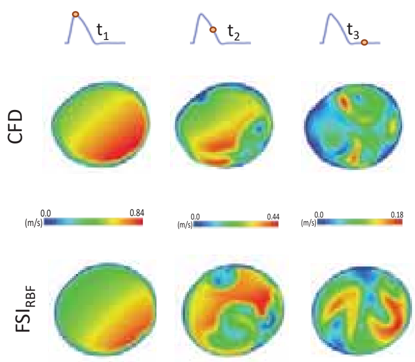


Figure 7

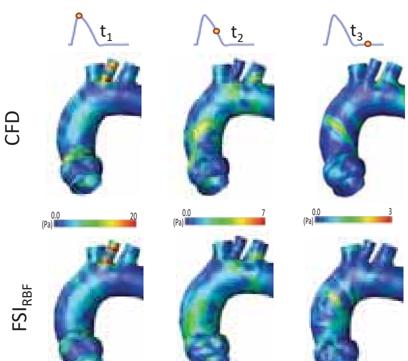


Figure 8

Conclusions – In this work a new strategy to simulate the thoracic aorta hemodynamics connected to its deformations during cardiac cycle was implemented. The RBF mesh morphing technique coupled with CFD transient simulation turned out to be an effective tool to investigate the effects of geometry modifications on the fluid dynamics. Therefore, it is possible to overcome the CFD rigid wall assumption and to the material properties definition required in the FSI simulations, with a less cost in terms of computational time.

[1] Capellini K. et al., Computational fluid dynamic study for aTAA hemodynamics: an integrated image-based and RBF mesh morphing approach. J Biomech Eng. 2018
[2] Boccadifuoco A. et al., Validation of Numerical Simulations of Thoracic Aorta Hemodynamics: Comparison with In Vivo Measurements and Stochastic Sensitivity Analysis., Cardiovasc Eng Technol 2018

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